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DRAWINGS ATTACHED.

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COMPLETE SPECIFICATION.

An Inverter for Operation at High Frequencies.

We, SOCIETE GENERALE DE CONSTRUCTIONS ELECTRIQUES ET MECANIQUES (ALSTHOM), a French Body Corporate, of 38, Avenue Kleber, Paris 16°, France, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The invention relates to inverters for operation at high frequencies, i.e. of the order of 10 KHz and above.

It is known that the frequency which it is possible to obtain with inverters utilising controlled rectifier elements of a given type, is limited both by the control re-establishing time of the rectifier element (interval of time which separates the instant when the current traversing the rectifier element has been brought to zero from that where this same controlled rectifier element has been sufficiently de-ionised in order to be able to support its full cut-out voltage in the direct sense without passing to the conductive state), and by the discharge time of this same controlled rectifier element (interval of time which separates the instant where the rectifier element has been rendered conductive from that where this same rectifier element has been sufficiently ionised in order to be able to set up its full current, either instantaneously for certain types of rectifiers or with a very high establishment slope $\frac{di}{dt}$ for other types).

Inverters of the "series" type are, from among the known inverter arrangements, the arrangements which permit the highest frequency to be obtained with a given type of controlled rectifier element.

The present invention has for an advantage that, by a modification in the series inverter, it permits the ratio between the sum of the discharge connecting the control re-establishing times, to be considerably increased by the duration of the period of the alternating output current. In some of the embodiments the invention, this ratio can even become higher than unity, this permitting much higher frequencies to be obtained than the limited frequency which is possible to obtain by using the same type of controlled rectifier elements in series inverters such as those which have been produced up to the present time. Moreover, the present invention permits the waveform of the alternating output current to be improved. In a series inverter of a known arrangement, an inductor and a capacitor, which constitutes a resonant circuit, are mounted in series in the A.C. connection of the inverter arrangement in the A.C. diagonal of a single-phase controlled rectifier bridge unit. Either the inductor or the capacitor, or both of them, may be supplied by the secondary winding or windings of one or two transformers whose primary winding or windings are in the same A.C. connection.

According to the invention there is provided an inverter with a series oscillating circuit for high frequencies comprising an assembly of a plurality of controlled rectifier elements forming at least one single-phase bridge of which one diagonal arranged for connection to a D.C. source, serves to supply direct current and the other diagonal connects in series each pair of opposite branches of the bridge of which one pair serves to supply one half wave of alternating current and the other pair serves to supply the other half wave, and a resonant circuit comprising a capacitor connected in the said other diagonal and an inductor connected in the said one diagonal

and permitting the current to be switched from the branches relating to one half wave to the branches relating to the other half wave with the inductor appearing in series with the said other diagonal. The inductor may be connected to the terminals of the secondary winding of a transformer having its primary winding inserted in the said one diagonal. Each capacitor may be connected to the terminals of the secondary winding of a transformer having its primary winding inserted in the said other diagonal of each bridge. A saturable inductor may be inserted in series in the said other diagonal of each controlled rectifier bridge. A plurality of single-phase rectifier bridges may be supplied in parallel by the same said one diagonal in which the first-mentioned, or main, inductor is connected; these bridges then operating one after the other during the successive periods of the alternating current which circulates in the main inductance. A plurality of bridges, or groups of bridges supplied in parallel, may be associated so that the main inductor is connected in a common part of their said one diagonals, and that one half of these bridges, or groups of bridges, serves to supply a half-wave from the alternating current circulating in the main inductor, the other half of these bridges, or groups of bridges, serving to supply the other half-wave, the two direct current components being compensated at least approximately. The controls of the various controlled rectifiers are preferably effected at instants such that the arms which can offer the current an alternative route not passing through the main inductor, are never conductive simultaneously, or can be conductive only when the current deflection path or paths thus afforded each comprise at least one saturable inductor which is then in the non-saturated state and thus limits the slope of variation of the current to a relatively low absolute value.

It is known that in the operation of a series inverter, the capacitor is alternately charged in one direction and in the other. With the arrangements known up to the present time, the inductor and the capacitor connected directly in series, are traversed by the same alternating current and operate at the same frequency. In an arrangement embodying the invention, the two half-waves of opposite directions of the alternating current passing through the capacitor are shown by two half waves of current having the same direction in the D.C. supply diagonal, and consequently in the inductor which is inserted therein. Such half-waves of current with the same direction correspond to the superposition of a direct current and an alternating current, relatively rich in even harmonics, whose frequency is double the frequency at which the capacitor and the controlled rectifier elements operate. As it is this latter frequency which is limited by the discharge connecting times and control re-establishing times of the controlled rectifier elements, such an assembly, comprising a controlled rectifier bridge unit, an inductor connected in the diagonal arranged for connection to a D.C. source and a capacitor connected in the other, or A.C. diagonal, permits the limited frequency which it is possible to obtain from a series inverter utilising controlled rectifier elements of a different type to be doubled.

If a plurality of rectifier element bridges is supplied in parallel along a common diagonal connected to a D.C. source in which the main inductor is connected, and operate successively, one after the other, the frequency of the basic term of the current traversing the main inductor is equal to the operating frequency of the rectifier elements and capacitors, said frequency being multiplied by twice the number of bridges mounted in parallel.

The presence of a D.C. component in the current which circulates in the main inductor increases its effective value, and this can be a problem. It will be understood that it is possible to set up circuits associating a single inductor with two or more bridges or assemblies of single-phase controlled rectifier bridges so that the half-waves of unidirectional currents supplied respectively by the two halves of these bridges, or bridge assemblies, pass through the inductor in opposite directions. D.C. components are practically eliminated, and, if the controls applied to the controlled rectifier elements are such that the basic terms of the A.C. components are in phase, the even harmonics are in opposition and practically disappear.

The saturable inductors which can be connected in the circuits for charging and discharging the capacitors have for their object to limit to an admissible value the slope di/dt of establishment of the current in the controlled rectifier element during their discharge connecting time, and must be of appropriate values.

In order that the invention may be more clearly understood reference will now be made to the accompanying drawings showing some embodiments thereof, by way of example, and in which:—

Figure 1 shows a circuit diagram of an inverter embodying the invention and comprising a single rectifier bridge.

Fgure 2 shows a diagram of flux characteristics.

Figure 3 shows diagrams useful in explaining the operation of the embodiment of Figure 1.

Figures 4, 6, 7 and 9 show further embodiments, and

Figures 5, 8 and 10 show explanatory diagrams useful in explaining operation of the embodiments of Figures 4 and 6, Figure 7, and Figure 9, respectively.

Referring now to the drawings: Figure 1 shows an inverter embodying the invention, and comprising only a single rectifier bridge 1 constituted by four control rectifiers 2, 3, 4 and 5 provided with controlled electrodes such as 6 whose supply means are not shown. A D.C. source 7, of negligible internal impedance, having its positive and negative terminals, respectively referred to by the signs + and —, is connected in the D.C. diagonal 8 of the bridge 1. A main inductor 9, for example the heating coil of an induction furnace is also connected, in series with the source 7, in the diagonal 8. A capacitor 10 and a saturable inductor 11 are connected in series in the other diagonal 12 of the bridge 1.

In order to simplify the explanation, it will be assumed that the flux characteristic as a function of the current of the saturable inductor 11 has the appearance shown in Fig. 2. In this drawing the scale of the currents, shown on the abscissa, is considerably exaggerated. The characteristic is assumed to be composed solely of rectilinear parts. It comprises two parts ABC and DEF for which the variation is very rapid, sharp bends A, C, D and F at saturation and de-saturation, and two practically horizontal parts FCG and ADH for which further variations in current no longer produce any flux variation. The part ABC corresponds to increasing fluxes and part DEF to decreasing fluxes, the bends C and D to saturation and bends A and F to desaturation. In practice, the magnetic circuits, which include a very small air gap, are constructed of hypermagnetic material with a low coercive force and a rectangular hysteresis cycle characteristic, and have characteristics which differ only slightly from the idealised shape shown in Fig. 2.

The diagrams of Fig. 3 will enable the operation of the circuit arrangement shown in Fig. 1 to be more readily understood. In the upper part of Fig. 3, the curve $v10$ and $i10$, respectively, show the variations in the voltage at the terminals of the capacitor 10 and the current which passes through it. In the lower part, the curves $v9$, $i9$ respectively show the variations of the voltage at the terminals of the inductor 9 and the current which passes through it.

It will be assumed that the inverter is in operation for a fairly long time for stable operation to be achieved. Immediately before the instant $t1$, none of the controlled rectifier elements 2, 3, 4 and 5 is conductive and no current circulates. The capacitor 10 is charged to a voltage +VO, its left hand plate (as viewed) being positive with respect to its right hand plate; this direction of voltage is that which will be referred to as being the positive direction. The flux of the inductor 11 corresponds to point B of the flux characteristic plotted in Fig. 2.

At time $t1$, the rectifier elements 2 and 4 are rendered conductive and the capacitor 10 begins to discharge through the saturable inductor 11, the source 7, the inductor 9 and the two rectifier elements 2 and 4. The current circulates from right to left in the A.C. diagonal 12 of the bridge 1; this direction being that which will be taken as being the positive direction of the current. The discharge of the capacitor takes a sinusoidal form. The frequency is fixed by the capacitance of the capacitor 10 and by the sum of the values of the inductances of inductors 9 and 11. This latter is very high, because the inductor 11 then operates in the part BC of the flux characteristic plotted in Fig. 2. The current $i10$ is established slowly and the voltage V10 lowers very little. At the instant $t2$ the current reaches the value $j2$ which corresponds to the bend in the saturation C of the flux characteristic and the value of the inductor 11 drops to a practically zero value. The inductor 11 is of such size that the interval of the time $t1$ to $t2$ is equal to or slightly higher than the discharge time connecting of the controlled rectifier elements 2, 3, 4 and 5. This time is that which is necessary for the rectifier elements to be sufficiently ionised in order to be able to carry their full current which is then being established with a considerable slope di/dt.

At time $t2$, the voltage $v10$ has reached a value V1, which is very little smaller than V0. The discharge then takes the sinusoidal mode corresponding to the capacitance of the capacitor 10, and to the value of the main inductor 9. The residual value of the inductor 11 is considered to be negligible. The voltage $v10$ at the terminals of the capacitor 10 is reversed and, at the instant $t3$, the current $i10$ has dropped to the value $j1$ which corresponds to the desaturation bend F, the voltage $v10$ then having reached a value —V2. The inductor 11 then operates in the part FE of the characteristic of Fig. 2. The current $i10$ varies very slowly and reaches zero at the instant $t4$. The state of flux of the inductor then corresponds to the point E of the characteristic of Fig. 2.

In stable operation, the energy supplied by the source 7 compensates exactly for the total losses in the various parts of the circuit: the inductors 9 and 11, the capacitor 10, the rectifier elements 2 and 4 and the connections. The energy stored in the

capacitor 10 is thus the same at instants $t1$ and $t4$. At instant $t4$, the voltage at the terminals of the capacitor 10 is thus equal to $-V0$.

For the foregoing period, the current $i9$ in the inductance 9 is obviously the same as the current $i10$ which passes through the capacitor 10. In Fig. 3 the curve $i9$ is thus a simple reproduction of the curve $i10$. The direction of the voltage which opposes the passage of the current supplied by the source 7 will be referred to as being the positive direction of the voltage $v9$ at the terminals of the inductor. Between the instants $t1$ and $t2$, the voltage $v9$ is positive and very low, because the value of the inductor 11 is great compared with that of the inductor 9. Between the instants $t2$ and $t3$ where the residual value of the inductor 11 can be considered as being negligible, the voltage $v9$ is practically equal to the voltage $v10$ which has been increased by the value E of the electromotive force of the source 7 and reduced by the voltage corresponding to the losses in the other parts of the circuit. Strongly positive at instant $t2$, the voltage $v9$ decreases, reverses and becomes strongly negative at instant $t3$ where it sharply diminishes in absolute value, the inductor 11 having reached the de-saturation bend F and having regained its full value. The voltage $v9$ naturally falls to a zero value at the instant $t4$ from which the main inductor is not traversed by any current.

During the interval of time $t3$, $t4$, the controlled rectifier elements which were traversed only by a very weak current, have begun to be de-ionised. Nevertheless, the controlled rectifiers 2 and 4 regain their control power only a certain time after the instant $t4$. The controlled rectifier elements 3 and 5 will be able to be rendered conductive only at instant $t5$ after an interval of time $t4$ to $t5$ which is sufficient for one to be certain that the rectifier elements 2 and 4 have indeed regained their control power.

The same process which has just been described is then repeated in the opposite direction. The discharge current $i10$ of the capacitor 10 is negative and reaches the value $-j2$ at the instant $t6$. The intervals of time $t5$ to $t6$ and $t1$ to $t2$ are equal, because the inductor 11 has operated in the part ED of its low characteristic which is symmetrical with the part BC, the voltage $v10$ reaching the value $-V1$. Between the instant $t6$ and $t7$ the curve $i10$ comprises a negative half wave which reproduces the positive half wave identically, apart from its sign, this positive half wave having been discharged between the instants $t2$ and $t3$. At the instant $t7$, the current $i10$ reaches the value $j1$ and the voltage $v10$ the value $+V2$. Between the instants $t7$ and $t8$, the intervals of time $t7$ to $t8$ and $t3$ to $t4$ being equal; the current $i10$ decreases, in absolute value, to zero. At the instant $t8$, the voltage $v10$ returns to its initial value $+V_0$.

However, the main inductor 9 inserted in the diagonal of the rectifier bridge connected to a D.C. source, is traversed by a unidirectional current. Between the instants $t5$ and $t8$, the current $i9$ always has an absolute value equal, but of opposite sign, to that of the current $i10$; i.e. the current $i9$ and the voltage $v9$ have at each instant values identical to those which they had at the corresponding instant of the interval of time $t1$ to $t5$. At the instant $t9$, after an interval of time $t8$ to $t9$ equal to the interval $t4$ to $t5$, the controlled rectifiers 3 and 5 have regained their control power and the rectifiers 2 and 4 are again rendered conductive. The above described cycle is repeated.

The current traversing the main inductance 9 and the voltage at its terminals have a frequency which is double that of the current passing through the capacitor 10.

The relatively large D.C. component which the current $i9$ comprises, causes a certain D.C. component to appear in the voltage $v9$. These components which can be a hindrance, are practically eliminated by suitably associating a plurality of rectifier bridges with a single inductor.

In the circuit of Fig. 4, two single-phase rectifier bridges 101 and 201, identical to the bridge 1 of Fig. 1, and comprising respectively the controlled rectifier elements 102, 103, 104, 105 on the one hand, 202, 203, 204 and 205 on the other hand, are connected in series. In their A.C. diagonals there are connected respectively the capacitors 110 and 210, identical to the capacitor 10 of Fig. 1 and the saturable inductors 111 and 211, whose size will not be the same as that of the inductor 11 of Fig. 1, as will be explained later. These two rectifier bridges are supplied with direct current by a source 107 whose extreme positive and negative terminals are referred to by the + and − signs and whose electromotive force 2E between the extreme terminals is divided equally between a median terminal, reference 0, and each of the end terminals. This source 107 is assumed to have a negligible internal impedance.

The upper part of the source 107 between the positive + terminal and median terminal 0, is connected in the diagonal 108 of the bridge 101 and the lower part between the median terminal 0 and the negative terminal −, is connected in the diagonal 208 of the bridge 201. In Fig. 4, each of the references 108 and 208 appears

twice in order to show clearly the two parts of each of the diagonals connected to D.C. The connection 14 between the median terminal 0 and the point 13 common to the current output terminal of the bridge 101 and to the current input terminal of the bridge 201, is common to the two diagonals 108 and 208 of the bridges 101 and 201. The main inductor 109, for example the coil of an induction furnace, is inserted in the connection 14, i.e. in the part connected in common to the two diagonals 108 and 208.

The diagrams of Fig. 5 enable the operation of the arrangement shown in Fig. 4 to be more clearly understood. In part A of Fig. 5, the lines $i110$ and $i210$ respectively show the currents traversing the capacitors 110 and 210. The phenomena are similar to those which are described with regard to Figs. 1 and 3. At the instant $t11$, the rectifier elements 102 and 104 are rendered conductive. The current $i110$ of the capacitor 110 increases first of all very slowly, because the inductor 111 is not saturated. The inductor 111 reaches its saturation point at the instant $t12$. It will be assumed that the characteristics of the rectifier elements used will result in the interval of time $t11$ to $t12$ being equal or approximately equal to the interval $t1$ to $t2$ of Fig. 3. This, as will be shown later on. leads to the inductors 111 and 211 being of a size or value which is different from that of the inductor 11 of Fig. 1. Between the instants $t12$ and $t13$, the capacitor 110 is discharged and becomes charged again in reverse direction as happened to the capacitor 10 of Fig. 1, between the instants $t2$ and $t3$ of Fig. 4. The representative curve of the current $i110$ has the same form as that of the current $i10$ between the instants $t2$ and $t3$. At the instant $t13$, the inductor 111 reaches its de-saturation bend and the current $i110$ decreases slowly in order to reach zero at instant $t14$. The rectifier elements 103 and 105 are rendered conductive at instant $t15$, the interval of time $t14$ to $t15$ having been determined in order that at instant $t15$, the rectifiers 102 and 104 have regained their control power. As in the case of Figures 1 and 3, the same phenomena are repeated but with a change of sign in the current $i110$. The instants $t16$, $t17$ and $t18$ of Fig. 5 correspond to instants $t6$, $t7$ and $t8$ of Fig. 3. At the instant $t19$ (which corresponds to the instant $t9$ of Fig. 3), the rectifiers 102 and 104 are again rendered conductive and the preceding cycle is repeated. In part B of Fig. 5, the wire $i108$ shows the current which circulates in the D.C. diagonal 108 of the rectifier element bridge 101.

In part A of Fig. 5, the diagram $i210$ shows the current which traverses the capacitor 210 in the A.C. diagonal 212 of the bridge 201. The duration of the period of the currents $i110$ and $i210$ is equal to the interval of time $t11$ to $t19$ or, this amounting to the same thing, the double the interval $t11$ to $t15$. The controls applied to the rectifier elements 202 to 205 of the bridge 201 are shifted by a quarter of this period with respect to the controls applied to the corresponding elements 102 to 105 of the bridge 101. The current $i210$ is itself also shifted by a quarter of a period with respect to the current $i110$. In the case of Fig. 5, the current $i210$ is advanced with respect to the current $i110$, but it could equally well be retarded. For the operation of the bridge 201, the instants $t21$, $t22$, $t23$, $t24$, $t25$, $t26$, $t27$ and $t28$, correspond respectively to the instants $t11$, $t12$, $t13$, $t14$, $t15$, $t16$, $t17$ and $t18$. The diagram of the current $i208$ which circulates in the diagonal 208 of the bridge 201 is plotted in part B of Fig. 5. The current $i209$ which passes through the main inductor 109 is equal to the difference between the two currents $i108$ and $i208$. Its representative curve is plotted in part C of Fig. 5, whilst in part D there is plotted the representative curve of the voltage $v109$.

It will be noted that, in the example just described, the intervals of time such as $t13$ to $t16$ during which the inductor 110 is not saturated, or $t23$ to $t26$ during which it is the inductor 210 which is not saturated, are a little longer than the intervals such as $t16$ to $t17$, or $t26$ to $t27$. The result is that during the intervals of time such as $t13$ to $t26$ or $t26$ to $t14$ when the rectifier elements 102 and 104 of the bridge 201 are in the conductive state at the same time as the elements 203 and 205 of the bridge 201, there is provided a current deflection path which does not include the inductor 109. The rate of variation of the current thus deflected is limited to a relatively low value, either by the two inductors 111 and 211, or by at least one of them not being saturated and so having its full value. Such an arrangement avoids current peaks which could be both high and established very quickly and which might be deleterious either to the rectifier elements or to the capacitors. Such arrangements are preferable but not essential. For the same reason, if the circuits did not comprise saturable inductors such as the inductors 111, 211, it would be preferable that the rectifier elements for example 203 and 205 of the bridge 101 are rendered conductive only after the capacitor 110 is charged to its full voltage and after the current has been brought to zero in the rectifier elements, for example 102 and 104 of the bridge 201.

The preceding explanations show why the saturable inductors 111 and 211 can have a different size or value from that of

the inductor 11 of Fig. 1. In the case of Fig. 1, during the interval of time such as interval $t1$ to $t2$ of Fig. 3, the inductor 11 had to carry the largest part of the sum of the electromotive force E of the source 7 and the charge voltage of the capacitor 10.

In the case of Fig. 4, during the interval of time $t11$ to $t23$ the inductor 111 will have to support the algebraic sum of the electromotive force E of the upper part of the source 107 of the charge voltage of the capacitor 110 and the voltage which appears at the terminals of the inductor 109 traversed by the current which circulates in the diagonal 212 of the bridge 201. This current constitutes the negative half wave of the current $i109$. At the instants in question, the above defined voltage is cut off in absolute value from the sum of the electromotive force E and the voltage at the terminals of the capacitor 110. If it is desired that the interval $t11$ to $t12$ of Fig. 5 is close to the interval of time $t1$ to $t2$ of Fig. 3, the inductors 111 and 211 of Fig. 4 will have a size or value which is less than that of the inductor 11 of Fig. 1.

It is noted that the representative curve of the current $i109$ which traverses the main inductor 109 is much more nearly sinusoidal than the representative curves of the currents $i110$ and $i210$, or the current $i10$ of Fig. 3, which correspond to those given by a conventional series inverter.

If the controls applied to the rectifiers constituting the bridges 101 and 201 are perfectly correct, if the values of the capacitors 110 and 210 are really equal, and if the characteristics of the saturable inductors 111 and 211 are identical, the current $i109$ will comprise neither D.C. component nor even harmonic terms. Such a situation is difficult to achieve and, in practice, the current $i10$ will normally comprise small D.C. components and even harmonic components, though these will not generally be harmful.

The use of a D.C. source provided with a centre voltage terminal such as source 107 of Fig. 4 is often suitable. The circuit shown in Fig. 6, avoids the use of such a source. In this arrangement, four controlled rectifier bridges 301, 401, 501, 601 provided with the capacitors 310, 410, 510 and 610 and with saturable inductors 311, 411, 511, and 611, similar to those which have already been used in the arrangements shown in Figs. 1 and 4, are themselves connected in a Wheatstone bridge. A main inductor 109 identical to that per the arrangement of Fig. 4 is connected in the A.C. diagonal 114 of this bridge between the common points 113 and 213, the former between the two rectifier bridges 301 and 601 connected in series, the latter between the rectifier bridges 401 and 501, also connected in series. It is noted that this diagonal is in fact a common part between the diagonal common to the two bridges 301 and 501, and the diagonal common to the two bridges 401 and 601. The D.C. supply source 307 whose internal impedance is assumed to be zero is arranged in the diagonal of the general bridge which is itself also a common part of all the diagonals connected to D.C. of the rectifier bridges 301, 401, 501 and 601.

If it is desired that the controlled rectifier elements 302 to 305, 402 to 405, 502 to 505, 602 to 605, which are assumed to be identical to those utilised in the preceding examples, operate under the same cut-off voltage and reverse voltage conditions, the source 307 should have an electromotive force equal to 2E.

The corresponding rectifier elements of the elementary rectifier bridges, for example 301 and 501 which constitute two opposite arms of the general bridge are rendered conductive simultaneously. For example, the rectifiers 303 and 305 of the bridge 301 are rendered conductive at the same time as the rectifiers 503 and 505 of the bridge 501. These rectifier elements discharge the same current simultaneously. The discharge of the rectifier elements 303 and 305 of the bridge 301 and 502 and 504 of the bridge 501 could also have been synchronised.

If it is desired to operate at the same frequency, to obtain the same current form and to have the same discharge connecting and control re-establishing times, as in the case of the circuit of Fig. 4, the capacitors 310, 410, 510 and 610 will have to be dimensioned for the same voltage as the capacitors 110 and 210 of Fig. 4 and must have double capacity. The saturable inductors 311, 411, 511, and 611 will be identical to the inductors 111 and 211 of Fig. 4.

Taking into account the preceding description, the operation of the assembly shown in Fig. 6 is the same as that of the assembly shown in Fig. 4 and the diagrams of Fig. 5 are applicable thereto.

The preceding examples enable the main inductor only to be operated at a frequency double that at which the rectifier elements and the capacitors operate.

The working frequency may be increased by raising in parallel a plurality of rectifier bridges and by causing them to discharge in turn successive periods of the working current passing through the main inductor.

In the circuit shown in Fig. 7, the same D.C. source 7 as that which is utilised in the arrangement of Fig. 1, supplies the two controlled rectifier bridges 701 and 801 by their common diagonal 708 in which is connected the main inductor 709 which is, for

example, the coil of an induction furnace. The controlled rectifier elements 702 to 705 and 802 to 805 which constitute respectively the two bridges 701 and 801, are identical to the rectifier elements 2 to 5 used in the arrangement of Fig. 1. The inductor 709 has a value equal for example to one half of the value of the inductor of the circuit of Fig. 1. Capacitors which are assumed to be identical, 710 and 810, as well as saturable inductors 711 and 811 are respectively connected in series and inserted in the A.C. diagonals, 712 and 812 respectively, of the rectifier bridges 701 and 801. The capacities of the capacitors 710 and 810 are assumed to be equal to one half of that of the capacitor 10 of Fig. 1. On the other hand, the saturable inductors 711 and 811 are assumed to be identical to the inductor 11 of Fig. 1. The oscillation frequency of the circuits comprising on the one hand the inductor 709 and the capacitor 710, and, on the other hand, the inductor 809 and the capacitor 810, is thus one half of that of the circuit comprising the inductor 9 and the capacitor 10 of Fig. 1. It will then be assumed, in order to simplify the explanation, that the damping of the last of these circuits is double that of the first, this causing the different oscillations of these circuits to be damped in the same proportion at the beginning, for example, of a half period of their actual oscillation.

Under these conditions, the operation of the bridge 701 is completely similar to that of the bridge 1 of Fig. 1. For example the diagram of the current *i* 710 traversing the capacitor 710 plotted in Fig. 8 is similar to that of the current *i* 10 plotted in Fig. 3. In particular, following hypotheses made on the frequency and the damping of the oscillating circuits, the amplitude of the voltage in stable operation at the terminals of the capacitor 710 will have, for example, the same value V0 as in the case of the circuit of Fig. 1. The instants *t*31 to *t*39 of Fig. 8 correspond respectively to the instants *t*1 to *t*9 of Fig. 3. The intervals of time such as *t*31 to *t*32 of Fig. 8 and *t*1 to *t*2 of Fig. 3 are equal, since the voltages used are the same and since the saturable inductors 11 of Fig. 1 and 711 of Fig. 7, are identical. Similarly, the intervals of time such as *t*33 to *t*34 of Fig. 8 and *t*3 to *t*4 of Fig. 3 are equal for the same reason. On the other hand, the intervals of time such as *t*32 to *t*33 and *t*36 to *t*37 of Fig. 8 are equal to one half of the intervals of time *t*2 to *t*3 or *t*6 to *t*7 of Fig. 1. The duration of the period of the current *i* 710 is equal to the interval of time *t*31 to *t*39. The controls applied to the rectifier elements 802 to 805 of the bridge 801 are shifted by a quarter of a period, in advance in the case of the diagrams of Fig. 8, over those applied to the rectifier elements 702 to 705 of the bridge 701. The current *i* 810 which traverses the capacitor 810 is itself shifted by a quarter of a period over the current *i* 710. The half waves of the two currents *i* 710 and *i* 810 are each shown in the diagonal 708 and in the main inductor 709 by current waves of the same form, but all of the same direction. The representative curve of the current *i* 709 which passes through the main inductor 709 is plotted at *i* 709 in Fig. 8. This current comprises a basic term of frequency which is four times that at which the controlled rectifier elements 702 to 705 and 802 to 805 operate. The current *i* 709 comprises a D.C. component and harmonics, of which those of even rows are relatively high.

The D.C. components may practically be eliminated, as well as the even row harmonics, by generalising the arrangements of Figs. 4 and 6.

In the arrangement of Fig. 9, the same D.C. source 107 provided with its centre connection O which has already been used in Fig. 4, supplies through its upper part the two monophased rectifier bridges 901 and 1001 in the A.C. diagonals of which the capacitors 910 and 1010 and the saturable inductors 911 and 1011 are respectively located. Through its lower part, the source 107 supplies the two single-phase bridges, which are presumed to be identical to the two preceding bridges, 1101 and 1201 respectively, in the A.C. diagonals in which the capacitors 1110 and 1210 and the saturable inductors 1111 and 1211 are respectively located. The main inductor 909, for example the coil of an induction furnace, is placed in the connection 914, common part of the four diagonals 908, 1008, 1108 and 1208 connected to D.C. respectively of the four bridges 901, 1001, 1101 and 1201. It will be assumed that the controlled rectifier elements utilised, 902 to 905, 1002 to 1005, 1102 to 1105 and 1202 to 1205 are identical to those used in the preceding examples.

The operation of the assembly will be more readily understood by examining the diagrams of Fig. 10. In these diagrams the time scale is approximately twice that of the diagrams of Fig. 3, 5 and 8 whilst the current scale has been reduced.

The operation, for example, of the bridge 901 is similar to that of the bridge 1 of Fig. 1, described above with regard to Figs. 1 and 3 and referred again to in Figs. 4 and 5. The instants *t*41, *t*42, *t*43, *t*44, *t*45, *t*46 and *t*47 of Fig. 10 correspond respectively to the instant *t*1, *t*2, *t*3, *t*4, *t*5, *t*6 and *t*7 of Fig. 3 and *t*11, *t*12, *t*13, *t*14, *t*15, *t*16 and *t*17 of Fig. 5. Assuming that the rectifier elements utilised in the various arrange-

ments described have the same characteristics, and taking into account the voltage appearing at the terminals of the inductor 909, the saturable inductors 911, 1011, 1111 and 1211, are of such value that the intervals of time such as $t41$ to $t42$ and $t43$ to $t45$ of Fig. 10 are equal or differ only relatively little from the intervals of time such as $t1$ to $t2$ and $t3$ to $t5$ of Fig. 3, or $t11$ to $t12$ and $t13$ to $t15$ of Fig. 5.

As in the case of Fig. 5, where the duration of the period of the currents $i110$ and $i210$ respectively passing through the capacitors 110 and 210 was equal to double the interval of time $t11$ $t15$, in the case of Fig. 10, the duration of the period of the current $i910$ which passes through the capacitor 910 is equal to double the interval of time $t41$ to $t45$. The controls applied to the rectifier elements 1002 to 1005 which constitute the single-phase bridge 1001 are shifted by a quarter of the period of the current $i910$, for example lagging, in the case of Fig. 10, over those applied to the corresponding elements 902 to 905 of the bridge 901. The current $i1010$ which traverses the capacitor 1010 is itself also shifted by a quarter of a period over the current $i910$, as shown in Part A of Fig. 10. The two halve waves, one positive and the other negative, of each of the currents $i910$ and $i1010$ are shown by half waves of current of the same direction which circulate from right to left, i.e. in the positive direction, in the connection 914 common to the four diagonals connected to D.C., respectively 908, 1008, 1108 and 1208 of the four bridges 901, 1001, 1101 and 1201 and in the main inductor 909.

Similarly, the controls applied to the rectifier elements 1102 to 1105, of the single-phase bridge 1101 are shifted by one eighth of a period, lagging in the case of Fig. 10, over those applied to the corresponding rectifier of the bridge 910; those applied to the rectifier elements 1202 to 1205 of the bridge 1201 are phase shifted by three eighths of a period over those of the corresponding rectifiers of the bridge 901. The currents $i1110$ and $i1210$ passing respectively through the two capacitors 1110 and 1210 are also phase shifted by one-eighth and three-eighths of a period with respect to the current $i910$, as is shown in part C of Fig. 10. The two half waves of these two currents are shown by half waves of current of the same direction, but which circulate this time from left to right i.e. the negative direction, in the connection 914 and in the main inductor 909.

The total current which circulates in the inductor 909 is equal to the sum of the two currents $i910$ and $i1010$ from which the sum of the two currents $i1110$ and $i1210$ has been set apart. This current is shown by the diagram $i909$ plotted in part C of Fig. 10, it has a frequency four times the working frequency of the controlled rectifier elements 902 to 905, 1002 to 1005, 1102 to 1105 and 1202 to 1205 and the capacitors 910, 1010, 1110 and 1210. Each of the successive half waves of the current $i909$ corresponds, essentially to the successive discharges of the different rectifier bridges and to the successive discharges in one direction or the other of different capacitors.

It will be noted that in the example which has just been described, the capacitance of the capacitors which are assumed to be identical (910, 1010, 1110, and 1210) and the value of the inductor 909 has been chosen so that the duration of a half period of the actual oscillation of the resonant circuit constituted by the inductor 909 and by one of the capacitors 910, 1010, 1110 and 1210 is slightly lower than one eighth the duration of the period of the currents $i910$, $i1010$, $i1110$ and $i1210$. Thus, during the intervals of time such as $t42$ to $t69$ during which the rectifier bridge 901 has its rectifier elements 902 and 904 in the conductive state at the same time as the bridges 1101 and 1201 has respectively, their rectifier elements 1102 and 1104 for the former, 1203 and 1205 for the latter, also in the conductive state, or $t69$ to $t52$ for which the rectifier elements 902 and 904 of the bridge 901 and 1102 and 1104 of the bridge 1101, are conductive simultaneously and offer current deflection paths which do not pass through the main inductor 909, these deflection paths comprise at least one of the saturable inductors in the non-saturated state. This limits the absolute value of the rate of variation di/dt of these deflection currents to a relatively moderate value. These conditions are preferable but are not be absolutely essential, as has been explained above with regard to Figs. 4 and 5. Similarly, if the circuits did not comprise saturable inductors, it would be preferable that neither of the two rectifier bridges 901 and 1001 can discharge current at the same time as any one of the two bridges 1101 and 1201.

In the examples of Figs. 7 and 9, use has been made of the arrangements of two controlled rectifier bridges which operate successively in the course of different periods of the current passing through the main inductor, the assembly constituted by the bridges 701 and 801 in the case of Fig. 7, the two arrangements of bridges, 901 and 1001 on the one hand, 1101 and 1201 on the other hand in the case of Fig. 9.

Assemblies of 3 or, generally, *n*, rectifier bridges each operating for its turn during the successive periods of the current passing through the main inductor are feasible. The frequency of this current would then

be six times or, generally, $2n$, times the working frequency of the rectifier elements and the capacitors.

In the same way as the diagram of Fig. 9 is a generalisation of that of Fig. 4, the diagram of Fig. 6 can also be generalised. It is sufficient for this purpose to replace each of the four rectifier bridges used in Fig. 6 by an arrangement of 2, 3 or n bridges supplied in parallel and operating in turn during the successive periods of the current passing through the main inductor.

The examples described may be modified in various ways. In particular, the saturable inductors arranged in series with the capacitors in the A.C. diagonals of the rectifier element bridges can be completely or partially eliminated. They may also be located other than in the A.C. diagonal, for example in the diagonal connected to D.C. or directly in series with each or with only one part of the controlled rectifier elements. Magnetic couplings between various saturable inductors are also possible.

In the examples which have been described, the main inductor is inserted directly in the diagonal connected to D.C. or in a common part of the similarly-connected diagonals of a plurality of rectifier element bridges. It will be apparent that in all these examples, the main inductor can be replaced by the primary winding of a transformer whose secondary winding supplies another main inductor whose impedance would not suit direct supply.

The capacitors themselves may also be supplied by the secondary windings of transformers whose primary windings are inserted in the A.C. diagonals of the controlled rectifier bridges.

WHAT WE CLAIM IS:—

1. An inverter with a series resonant circuit for high frequencies comprising an assembly of a plurality of controlled rectifier elements forming at least one single-phase bridge of which one diagonal, arranged for connection to a D.C. source, serves to supply direct current and the other diagonal connects in series each pair of opposite branches of the bridge of which one pair serves to supply one half wave of alternating current and the other pair serves to supply the other half wave, and a resonant circuit comprising a capacitor connected in the said other diagonal and an inductor connected in the said one diagonal and permitting the current to be switched from the branches relating to one half wave to the branches relating to the other half wave with the inductor appearing in series with the said other diagonal.

2. An inverter as claimed in claim 1, wherein a saturable inductor is connected in series in the said other diagonal of the or each, controlled rectifier bridge.

3. An inverter as claimed in claim 1 or 2, wherein a plurality of said single-phase rectifier bridges are supplied in parallel by a common diagonal arranged for connection to a D.C. source in which the first-mentioned inductor is connected, said bridges being operative one after the other during successive periods of said alternating current for circulation in the first-mentioned inductor.

4. An inverter as claimed in claim 1, 2 or 3, wherein a plurality of said bridges, or groups of bridges, supplied in parallel, are associated so that the first-mentioned inductor is connected in a common part of their said one diagonals, and one half of said bridges or groups of bridges supplies a half wave of said alternating current for the first-mentioned inductor, the other half of said bridges or groups of bridges supplying the other half wave, so that components of the direct current are substantially compensated.

5. An inverter as claimed in claim 4, wherein the various controlled rectifiers are arranged to be controlled at instants such that the arms which can offer current a deflection path not passing through the first-mentioned inductor are never conductive simultaneously.

6. An inverter as claimed in claim 4 with claim 2, wherein the various controlled rectifiers are arranged to be controlled at instants such that the arms which can offer current a deflection path not passing through the first-mentioned inductor are rendered conductive simultaneously only when the resulting deflection path or paths thus opened comprise at least one said saturable inductor which is then in the non-saturated state so as to limit the rate of variation of the alternating current.

7. An inverter as claimed in any one of the preceding claims, wherein the first-mentioned inductor is connected to the terminals of a secondary winding of a transformer having its primary winding connected in the, or the common, said one diagonal.

8. An inverter as claimed in any one of the preceding claims, wherein the, or each, capacitor is connected to the terminals of a secondary winding of a transformer having its primary winding connected in the, or each, said other diagonal of the, or each, controlled rectifier bridge.

9. An inverter, substantially as hereinbefore described with reference to Figures 1 or 4 or 6 or 7 or 9 of the accompanying drawings.

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Sheet 1

fig.1

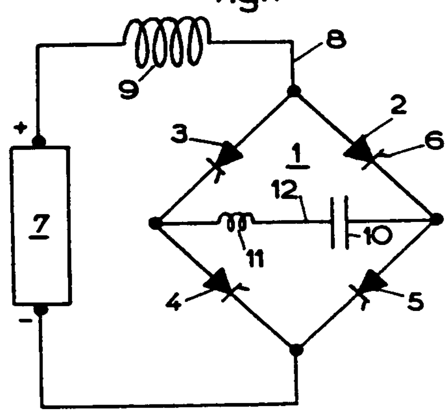

fig.2

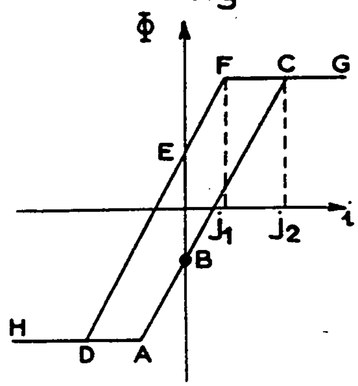

fig.3

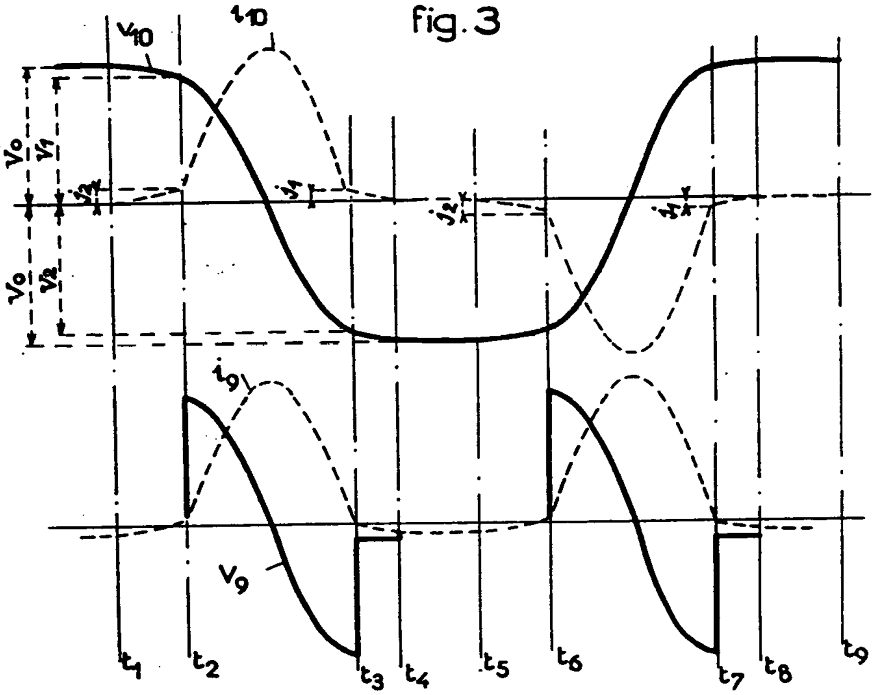

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Fig.4

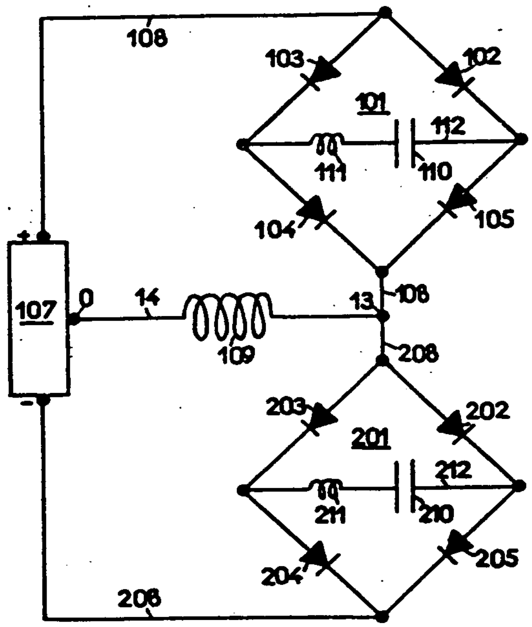
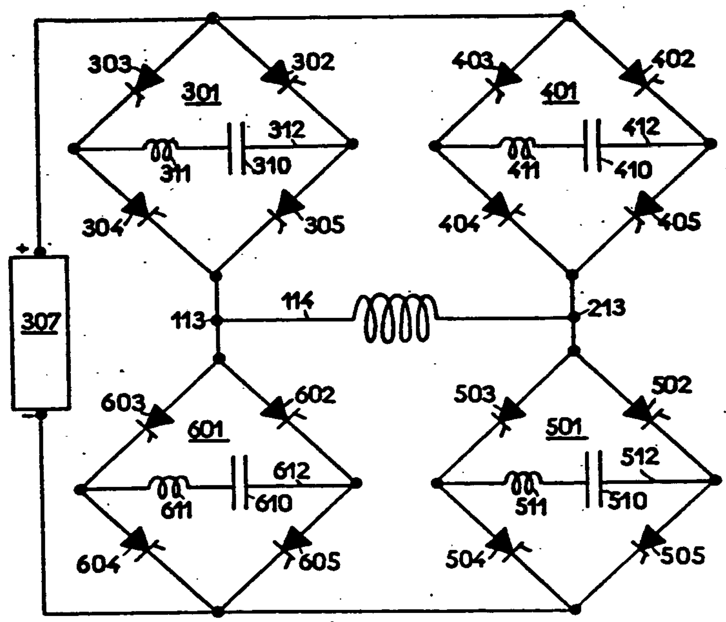


Fig.6



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Sheet 3

fig.5

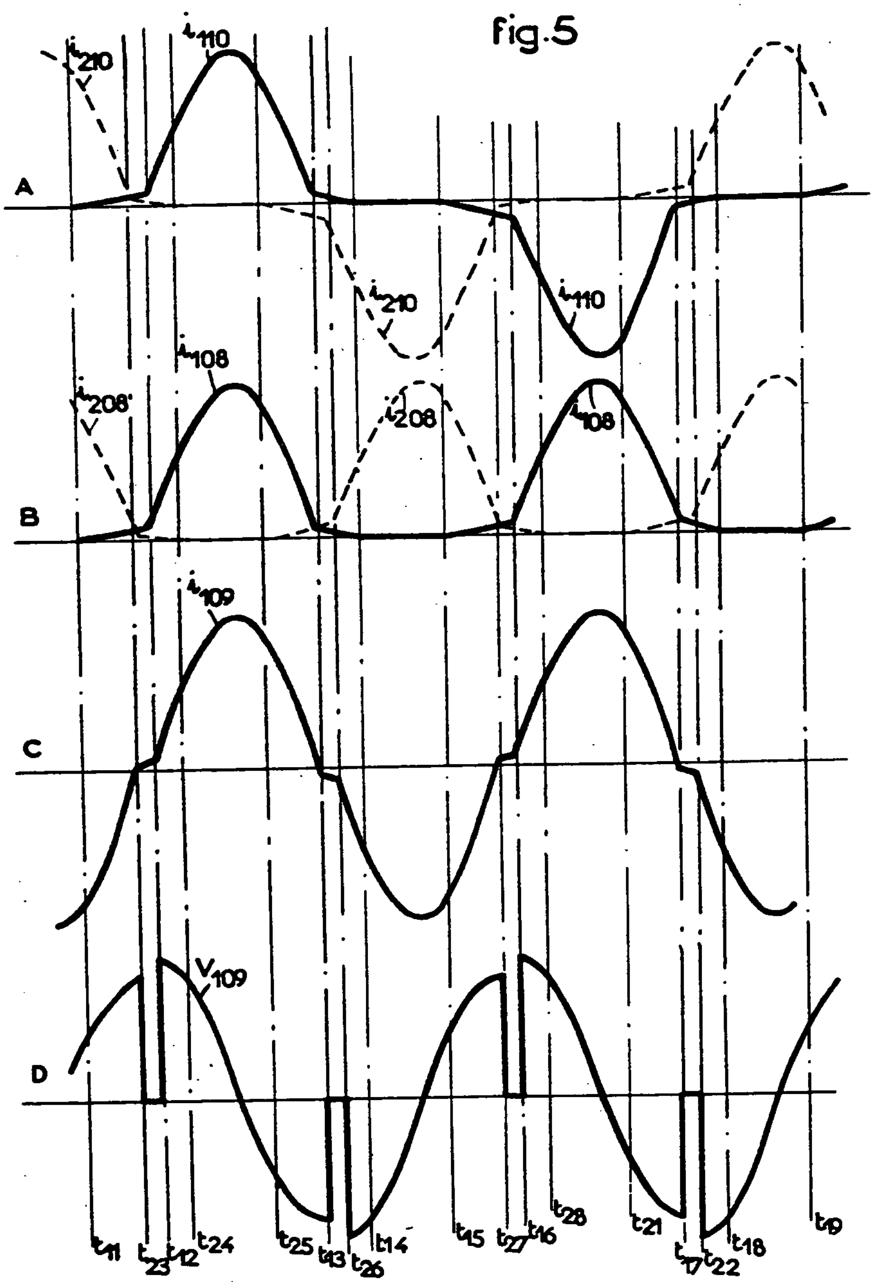

fig.7

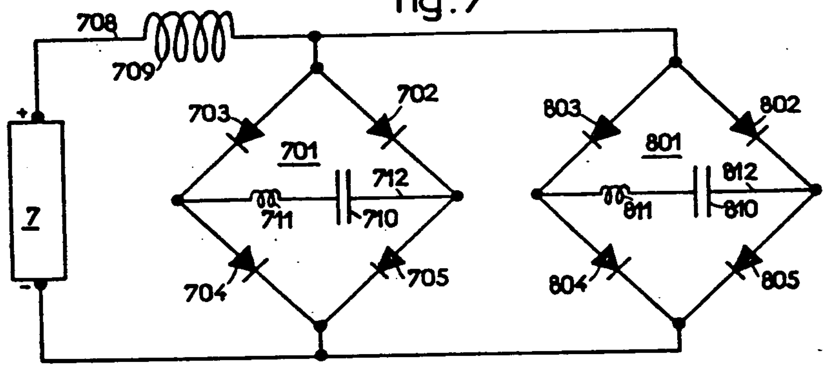
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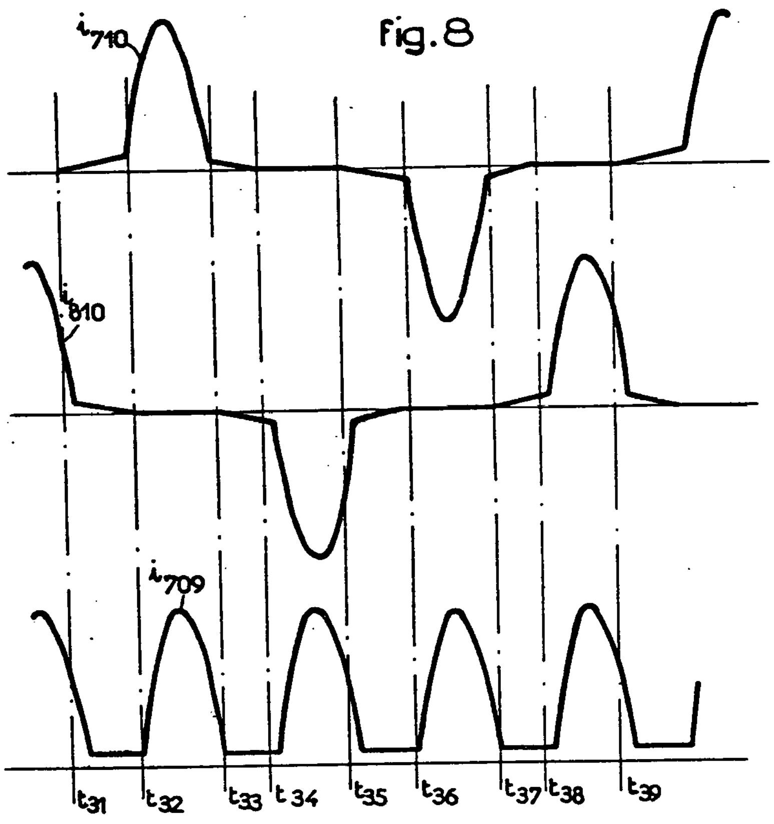
fig.8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Sheet 5

Fig.9

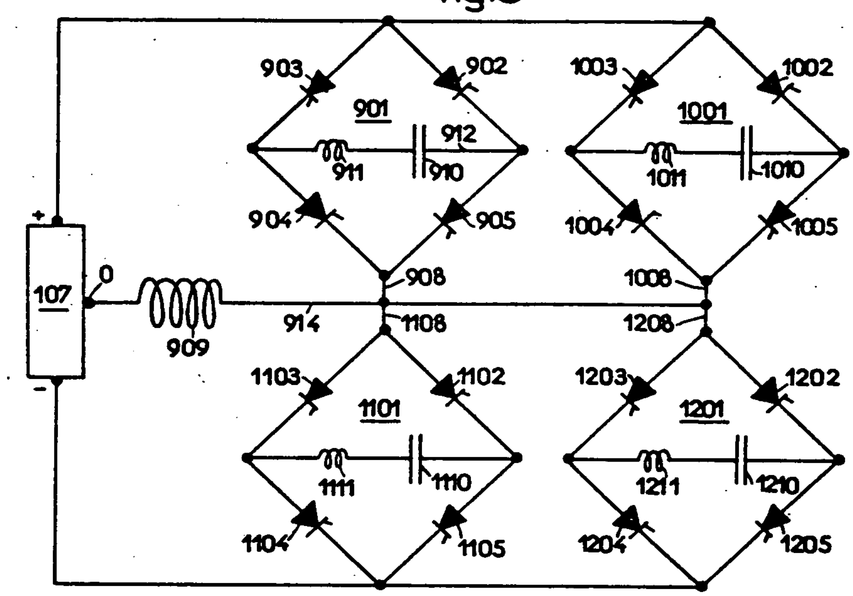

Fig.10